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CENTRIFUGE TESTING OF A PARTIALLY-CONFINED FC-72 SPRAY (POSTPRINT)

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Centrifuge Testing of a Partially-Confined FC-72 Spray

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ABSTRACT

The effects of elevated acceleration fields on spray cooling heat transfer are discussed in this paper. Spray cooling has proven to be one of the most efficient methods of heat removal. This technology is being transitioned into more advanced applications, such as fighter aircraft that must withstand a wide range of variable acceleration-induced body forces. Heat transfer associated with closed-loop spray cooling will be affected by acceleration body forces, the extent of which is not yet known. To test these various effects, an eight-foot-diameter centrifuge table will be outfitted with a spray cooling system to test for the effects associated with elevated gravity.

INTRODUCTION

BACKGROUND

The More-Electric Aircraft initiative has resulted in lower procurement costs, increased aircraft ranges and decreases in the turnaround time for both commercial and military aircraft. The following is a list of current airframes that benefit from MEA technology: F-35, Global Hawk, Predator, F-22, X-45 and Boeing 787 [1]. The goals of the initiative are to enhance system reliability, survivability, reduce weight and lower life cycle costs. The benefits of MEA, however, do come with a price. In the past, where hydraulic fluid was used to extract waste heat from various components, waste heat could be collected centrally and dumped overboard via air-to-air heat exchangers.

New programs that exacerbate the difficult thermal management issues include directed energy weapons (DEWs), such as high-energy lasers (HEL) and high power microwaves (HPM), and high-temperature, high-efficiency silicon carbide electronic packages. DEWs have resulted in unprecedented requirements for energy generation, distribution and storage, with vastly increased demands on proposed thermal management systems. With HEL, the isothermality of the diodes and gain media of the solid state lasers is critical to the performance and reliability of the lasers. In the HPM construct, the duty cycle includes steady-state and dynamic portions, each of which has unique thermal management requirements. Silicon carbide power switch modules may be used in power distribution, conditioning and utilization equipment. While higher temperatures may allow waste heat to be dumped overboard through the aircraft skin, the restrictions within the internal volumes available within the airframe may make this difficult, resulting in the necessity of an intervening thermal management device to link the SiC component to the aircraft skin. Possible solutions to these thermal management demands include both active and passive methods: chilling the aircraft fuel (which is used as a heat sink) prior to takeoff, jet impingement cooling, spray cooling, heat pipes, loop heat pipes, carbon foam impregnated with phase-change materials, and combinations of the above technologies.

Passive systems, such as heat pipes, have been tested with increased body forces to show the effects of acceleration on heat transfer [2]. Thomas et al. [3] conducted elevated gravity experiments on a heat pipe to simulate the irregular, non-steady flight pattern of typical aircraft flight profile. Sinusoidal waveforms with frequencies ranging from .01-.2 Hz with an acceleration loading of 1.1-9.8 g were tested. A very similar approach must be taken with any thermal management technology, including spray cooling. After steady state data is taken and verified, transient “flight profile” testing must be done to ensure the practicality of higher heat flux cooling technology for aerospace use. Gu et al. [4] conducted reduced gravity and elevated gravity experiments to help prove viability of pulsating heat pipes (PHPs) for space applications. The PHPs, filled with R-114, proved to work better in the absence of gravity but worse in elevated gravity, depending on orientation.

Pool boiling has been extensively studied under various body forces. Lee et al. [5] conducted experiments in reduced and elevated gravity flight testing as a comparison to the very detailed pool boiling curves in terrestrial conditions. The boiling experiment showed that under reduced gravity conditions, the critical heat flux is significantly reduced.

Spray cooling, an active system, also has the two-phase advantage, where the latent heat of vaporization removes a large amount of heat that single phase systems cannot. Although both two-phase techniques, spray cooling can be much better than pool boiling because the vapor generated at the heater surface is more easily removed [6]. Since FC-72 will be used as the coolant the heat flux removal cannot compete with other working fluids such as water. Because of the electrical component testing and application, a dielectric is necessary [7]. The present paper will focus on the use of spray cooling technology for an aircraft environment.

APPLICATIONS

Spray cooling has been used in a variety of applications for many years, such as continuous metal forming, roof cooling, cryogen spray cooling (CSC), and extended tool life in machining. The CSC process uses spray cooling to cool a human's skin while undergoing some types of laser surgery [8]. Somewhat recently, it has been used for high power density electronics cooling such as laser diodes, power supplies, power converters, electric motors, motor drives, wide band-gap (WBG) semiconductors, computer mainframes, and aviation/automotive electronics. Today's high powered lasers are generating enormous amounts of waste, leaving about half of the input energy as waste heat. Any Airborne Laser (ABL) will not only need high heat flux removal at terrestrial conditions, but also at elevated and reduced gravity conditions, to account for various airplane flight patterns. For this reason, spray cooling has also been proposed for microgravity situations, to perhaps extend the ABL's capability to reduced gravity flight and even outer space [7]. However, very little information is available in the open literature concerning spray cooling in the elevated acceleration fields present on fighter aircraft (up to 9-g's). Some issues that need to be addressed are the potential for significant enhancement of the heat transfer due to favorable removal of the thin liquid film on the surface to be cooled.

EXPECTED RESULTS

Sone et al. [9] and Yoshida et al. [10] showed that during microgravity (using FC-72), the critical heat flux (CHF) increased by 14% at the center of the heater. Their studies also showed a decrease in heat transfer along the peripheral due to the reduction in gravity. At elevated gravity, the heat transfer ability may decrease across the entire surface. Perhaps the fluid will, under elevated gravity, be "pulled" closer to and then swept off of the heater. This effect would show an increase in heat transfer. On the other hand, the vapor bubbles may become trapped on the heater leading to a superheated and lowered CHF condition.

The objective of this paper is to describe an experiment that will be used to determine the effects of elevated acceleration fields on spray cooling performance. Using a thick film heater mounted atop a glass pedestal within a spray cooling chamber mounted on a centrifuge table, the heat transfer coefficient due to the spray of FC-72 onto a heated surface will be determined by varying the coolant flow rate, the coolant subcooling, the heat input to the surface, and the radial acceleration on the table. This report documents the status of the experimental design and the proposed method of gathering and reducing the experimental data.

EXPERIMENTAL SETUP

CENTRIFUGE FACILITY

The purpose of the experiment is to examine spray cooling performance in an elevated body-force environment using a centrifuge table located at the Air Force Research Laboratory located at Wright-Patterson AFB (AFRL/PRPS), as shown in Figure 1.

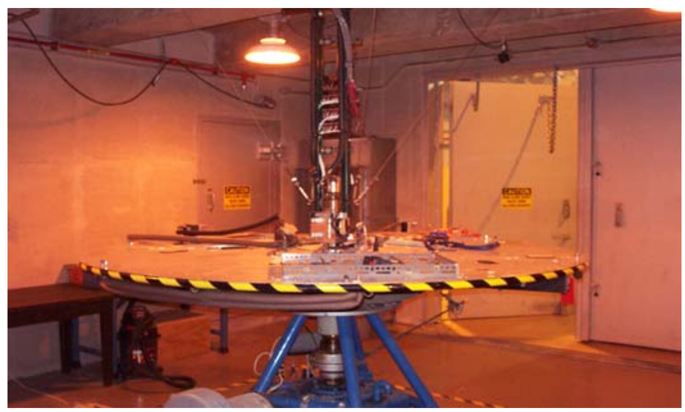

Figure 1. High-G test facility at AFRL.

The 8-foot-diameter horizontal centrifuge table is driven by a 20-hp dc motor. The acceleration field near the spray-cooled surface is measured by a triaxial accelerometer. The acceleration field at the face of the pedestal is calculated from the readings of the accelerometer using a coordinate transformation.

Electrical power is supplied to the thick-film resistance heater by a precision power supply through power slip rings to the table, as shown in Figure 2. These slip rings were separated from the instrumentation slip rings to reduce electrical noise. While the electrical current can be read directly using a precision ammeter (Magtrol 4612B), the voltage across the thick-film heater must be measured on the rotating table using the instrumentation slip rings because of the voltage drop between the control room and the table.

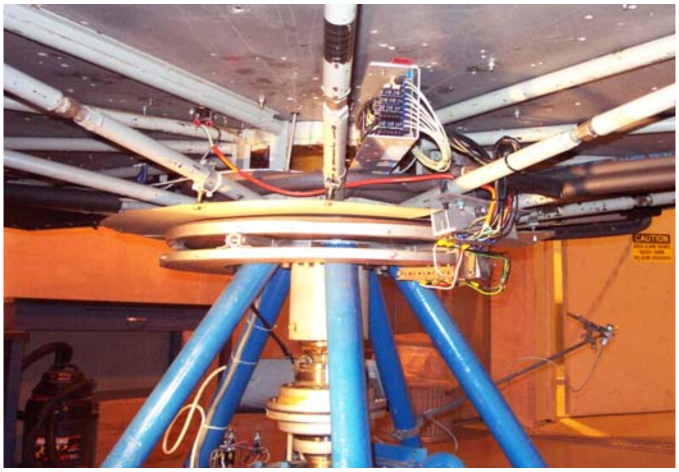

Figure 2. Centrifuge power and instrumentation slip rings.

Heat from the spray-cooling chamber is removed using an ethylene-glycol/water mixture that is delivered to the rotating centrifuge table via a double-pass hydraulic rotary coupling (Deublin). The temperature of the coolant is maintained at a constant setting by a recirculating chiller (Neslab HX-300). The mass flow rate of the coolant mixture is controlled using a high-pressure booster pump, which aids the low-pressure pump in the recirculating chiller.

Data from the spray cooling experiment are acquired through the custom-built forty-channel instrumentation slip ring, using a data acquisition system. Temperatures, pressures, mass flow rates, accelerations, and voltages are measured using a data acquisition mainframe (Agilent VXI E8408A) with a command module (Agilent E1406A), 5 ½ digit multimeter module (Agilent E1411B), and a 64-channel 3-wire multiplexer module (Agilent E1476A). In addition, the mass flow rate of the FC-72 coolant, the rotational speed of the centrifuge table and the heater power are controlled using an 8/16-channel D/A converter module (Agilent E1418A) coupled with a custom-designed Labview virtual instrument. Communication between the data acquisition unit and the computer is established using a general purpose interface bus (GPIB).

Gathering temperature data from rotating machinery using slip rings presents unique problems. Firstly, when the thermocouple wires are connected to the wires leading to a slip ring, at least one extra junction is created, depending on the materials of the thermocouple wires. To avoid this problem, a Type E thermocouple amplifier was installed on the centrifuge table. This converts the millivoltage signals from the thermocouples to 0 to 10 volt signals without the creation of extra junctions. Another problem that is present when slip rings are used is electrical noise. This problem was reduced (not eliminated) by the use of a low-pass filter for each of the thermocouple signals coming from the table before the data acquisition system.

SPRAY COOLING EXPERIMENT

The main components of the spray cooling loop are the Spray Cooling Test Chamber (SCTC), the stationary ethylene-glycol coolant bath, and the liquid controlling reservoir.

The SCTC houses the most important heat transfer measurement devices as well as providing flow visualization and interactions. A digital camera will be mounted inboard to the SCTC, with the ability to record video, as well as to send the signal to a monitor inside the control room. A 6-in diameter, 3/8-in wall clear acrylic tube that is approximately 5 ½-in long is capped by two 6-in diameter aluminum plates that are 1-in thick. The aluminum plates hold the two copper coils that will house the ethylene glycol coolant used for controlling the vapor pressure within the chamber, as shown in Figure 3. On each aluminum cap resides a ½-in pin that is pressed into a bearing on the mounting support structure. This support structure, made of ½-in aluminum plates allows the chamber to rotate freely, automatically orienting the direction of the spray in line with the body force imposed by the spinning of the table. The support structure will be mounted directly to the aluminum plates of the centrifuge table on the outer hoop, with the axis of rotation of the bearing tangent to the outer edge of the table.

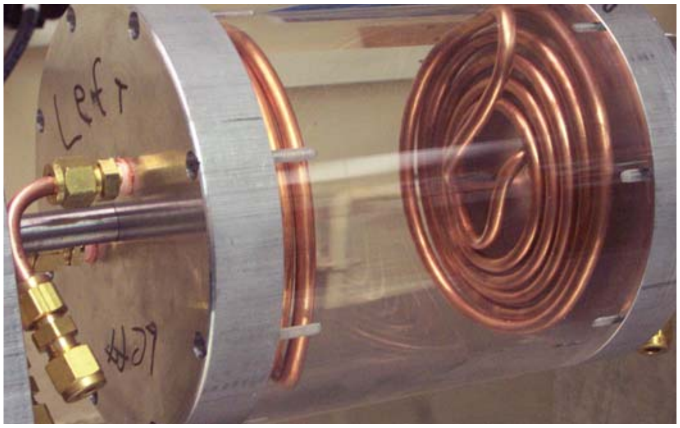

Figure 3. Spray cooling test chamer-condenser coils.

A 0 to 100 psia pressure transducer is mounted external to the chamber which is attached to a 3/8-in tube feeding into the central area of the chamber to measure the chamber pressure. An array of 5 type E thermocouples will be fed into the chamber, using a ¼-in NPT Conax fitting. These thermocouples will be positioned to get an accurate feel of the temperature distribution based on the liquid/vapor interaction inside the chamber. There will be one thermocouple near each of the copper coils on the ends, one in the middle of the chamber, and two mounted within the cap and annulus surrounding the heater leading to the fluid sump system.

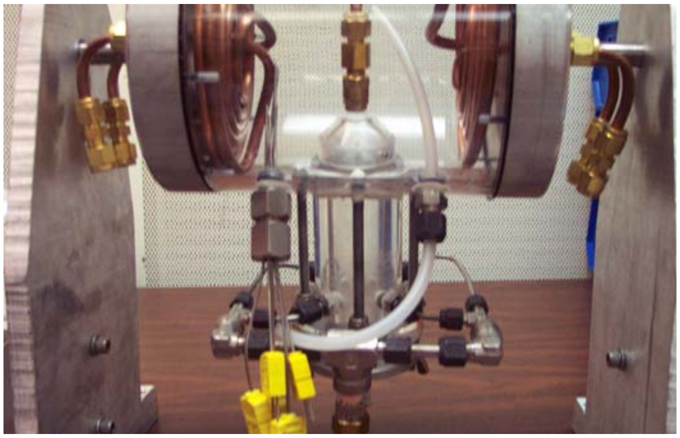

Figure 4. Spray cooling test chamber (SCTC).

The nozzle is a full cone spray nozzle with a 60 degree spray angle. The nozzle is mounted at a distance so the spray covers the entire surface, but minimizes overspray. The thick film resistance heater is mounted atop a 5/8-in glass rod pedestal. Within this rod there is a series of glass layers, each of which holds .010-in type E thermocouples (totaling seven). A clear acrylic annulus (1 1/8-in diameter) surrounds the glass rod, allowing for fluid to be pulled along its length towards the sump drain. Mounted on the top of the annulus is a clear acrylic cap that acts as a barrier for any liquid that is bouncing off of the heater surface. The cap also contains 2 through holes that allow any reflected liquid or any condensed vapor to reenter the annulus region and be drained out of the chamber. At the bottom of the annulus four 1/8-in tubes drain the fluid out of the chamber, pumping it back around the system, into the reservoir. The completed SCTC is shown in Figure 4.

The reservoir not only contains the extra fluid in the system, it also assures that the quality of the fluid passing through the tubing that leads to the nozzle is that of pure liquid. It does this by using a fluid control structure within the reservoir and the effects of gravity to keep pure liquid at the inlet of the reservoir drain. Because the reservoir also rotates, it allows for different fixed orientations or gravity to control where the drain is in relation to the body force.

Although there is no instrumentation in the reservoir, there are two flow meters, a pressure transducer on the inlet and outlet of both gear pumps, and thermocouples throughout the flow loop. The off-table mounted ethylene-glycol coolant bath will be used to control the temperature within the chamber and to condense and sub cool the fluid exiting the test chamber using a liquid/liquid heat exchanger. If a near vaporization temperature test condition is needed, a PID controlled preheater will be used. This heater will be used only to raise the working fluid temperature before entering the nozzle. A schematic of this flow diagram is shown in Figure 5.

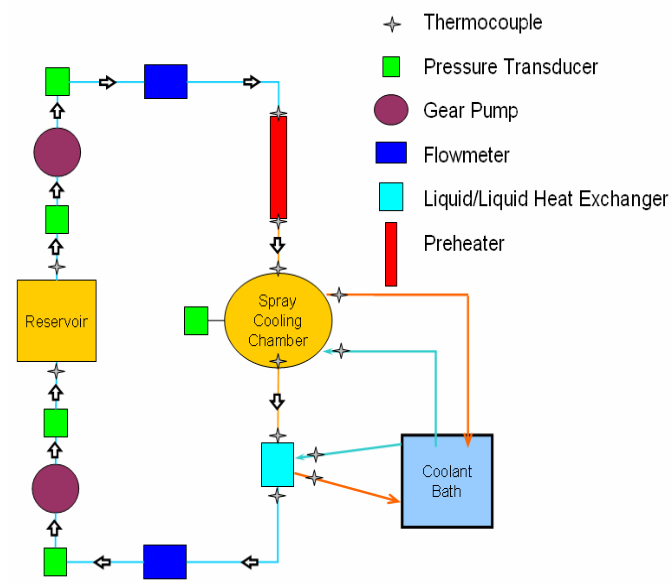

Figure 5. Schematic diagram of the spray cooling flow loop.

TEST PLAN

The experimentation will begin with terrestrial data sets, to verify the experimental setup and its ability to record accurate data. The two-phase curve (heat flux vs. wall superheat) associated with FC-72, the working fluid, is expected to shift due to the changes in gravity. A shift in the two-phase curve may also cause a shift in the CHF (determined from thermocouples placed directly beneath the heater surface), possibly increasing or decreasing the capable performance of a spray cooling system with varying body forces.

Parametric tests accounting for many factors will be run, such as flow rate, heater input, amount of subcooling, fluid inlet temperature to the nozzle, and of course the magnitude of the body forces due to gravity. For initial testing, the body forces will always be in the direction of the spray, normal to the heater surface. Table 1 shows the planned test parameters.

Table 1. Planned test parameters.

Constraint	Range	Step
Flow Rate	4-10 gph	2 gph
Heater Power	20-100 W/cm^2	10 W/cm^2
Sub Cooling	Δ0-Δ20 °C	5 °C
Inlet Temp	25-55 °C	10 °C
Gravity	1-10 g	1 g

CALIBRATED DATA

To ensure accuracy of the acquired data, systematic calibrations will be made. The most important data attained via the Agilent data acquisition system are the thermocouples and flow meters.

The accuracy of the flow meters will be maximized by verifying the manufacturer's calibrations using a mass flow setup. This setup will record the flow meter reading while FC-72 is pumped through it and into a beaker that will measure the volume over a set length of time. The flow rate found experimentally will then be used in the custom generated LabVIEW program where the data can be later used for heat transfer calculations.

Also, up to 16 type E thermocouples will be calibrated using a Hart Scientific 6330 Calibration Bath with a Hart Scientific 1502A resistance temperature detector (RTD). Using Dow Corning's 200.50 silicon oil, another custom LabVIEW setup will control the calibration bath temperature, record the steady state RTD temperature, and record each thermocouple's conditioned output voltage. From this data, ranging from 40-100°C, a linear fit can be made for each thermocouple, giving an accurate reading for the temperature.

The accuracy for the pressure, heater power, and acceleration will be determined once the entire system is completely assembled and ready to acquire data.

CONCLUSION

To be able to apply spray cooling to advanced aircraft applications, elevated gravity test data must be established. The most cost effective, with high accuracy, means of doing this is a spinning centrifuge table. A custom spray chamber and fluid support loop onboard a 10-g test platform will be able to show the dependencies of the various parameters (flow rate, subcooling, inlet temperature, and gravity) on the spray cooling heat transfer ability.

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